Shared Storage Resource Management Using Machine Learning and Control Theory

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QoS Challenge in Storage

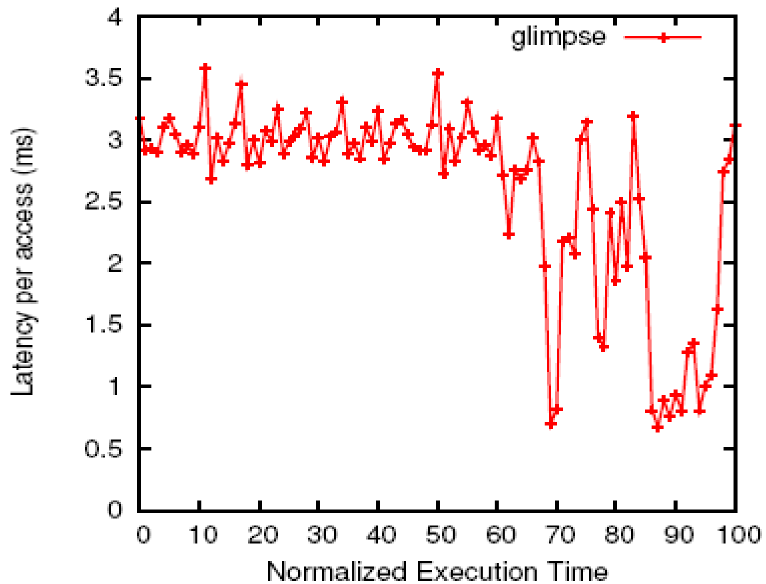
- Specification problem
  - How can we specify QoS?
    - Application level vs I/O level
    - Absolute vs relative
    - Hard vs soft
- Complex resource sharing patterns
  - Distributed resources, multi-server storage systems
  - Interactions among different types of resources
  - Hybrid storage architectures
- Measurement and enforcement
  - Where/how to enforce QoS?
  - Modeling and prediction [machine learning]
  - Tracking [formal feedback control]

Storage Cache Management Strategies

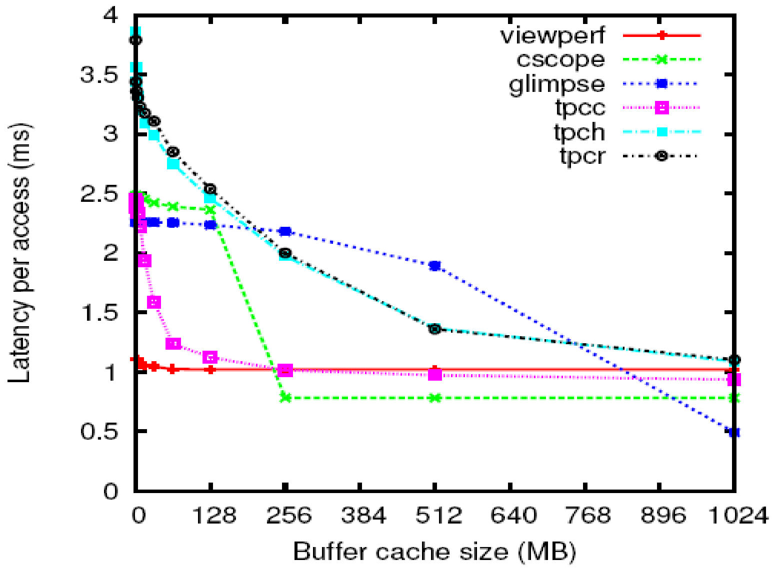
- No partitioning
  - Destructive interferences
- Equal (fair share) partitioning
  - Isolation, underutilization
- Static unequal partitioning
  - Isolation, lack of dynamic adaptation
- Dynamic adaptive partitioning

Motivation for Dynamic Scheme

Variation with Time



Variation with Cache Size



- Changing cache requirements of applications during execution
- Different saturating points with increasing cache sizes
- Motivates dynamically allocating cache based on application characteristics

Challenges in Dynamic Cache Space Management

- **Goals:** (1) Satisfy QoS for all applications
  (2) Improve performance

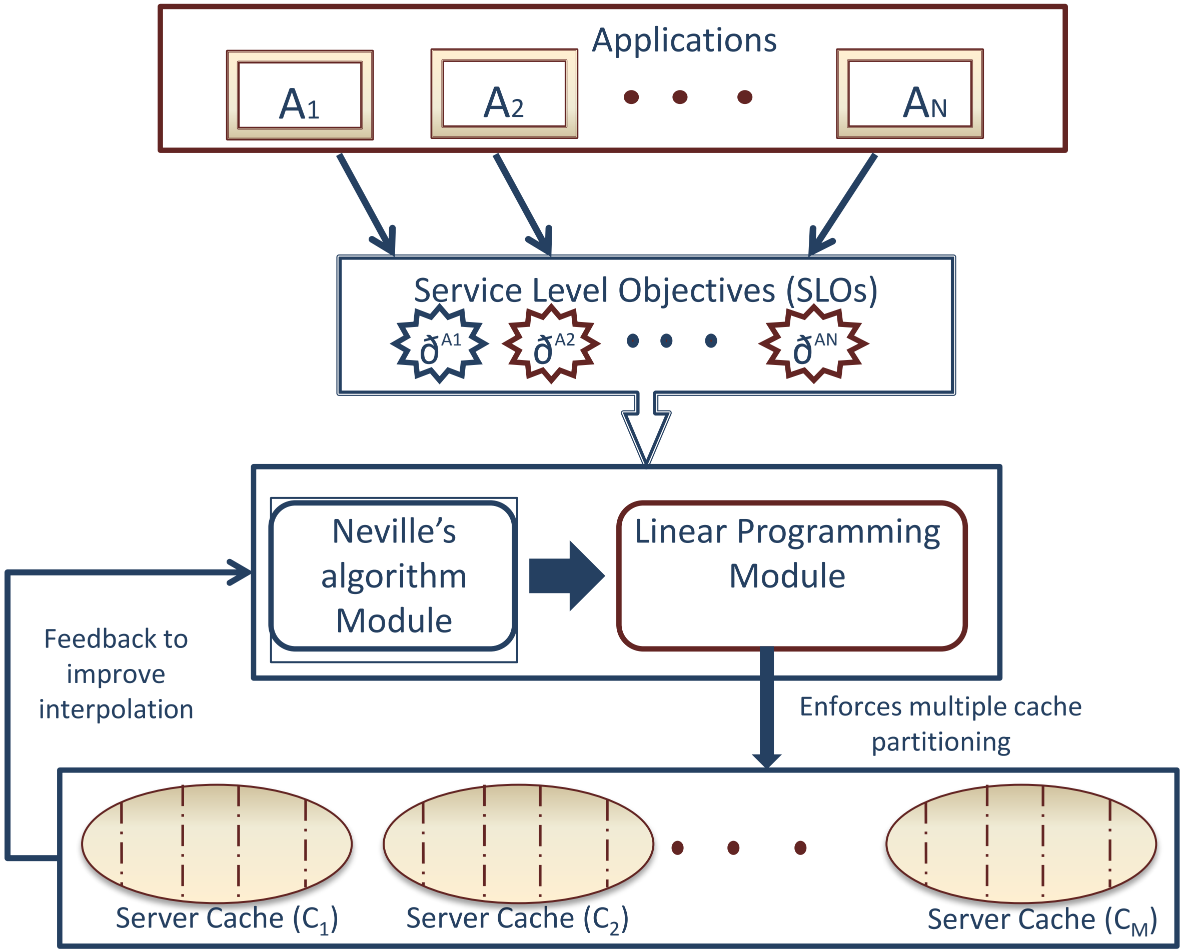
- How to partition the cumulative cache space across competing applications?
  (Neville's Algorithm)

- What would be the cache allocation across each of the available server caches for each application?
  (Linear Programming)

- How would the cache allocations adapt to dynamic modulations in cache requirements at runtime?
  (Feedback in every enforcement interval)

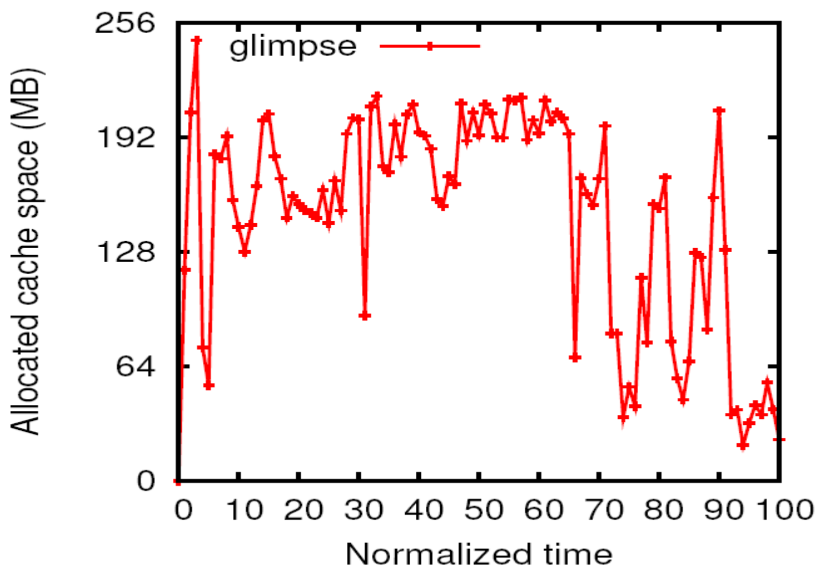
- How to provide performance guarantees and satisfy service level objectives (SLOs) of the applications ?
  (SLOs input to Neville's Algorithm)

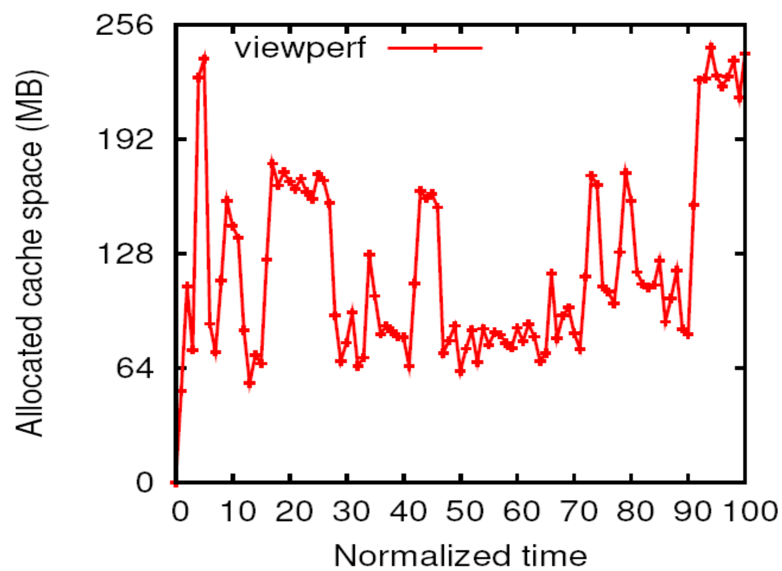
Overview of Storage Cache Partitioning Strategy

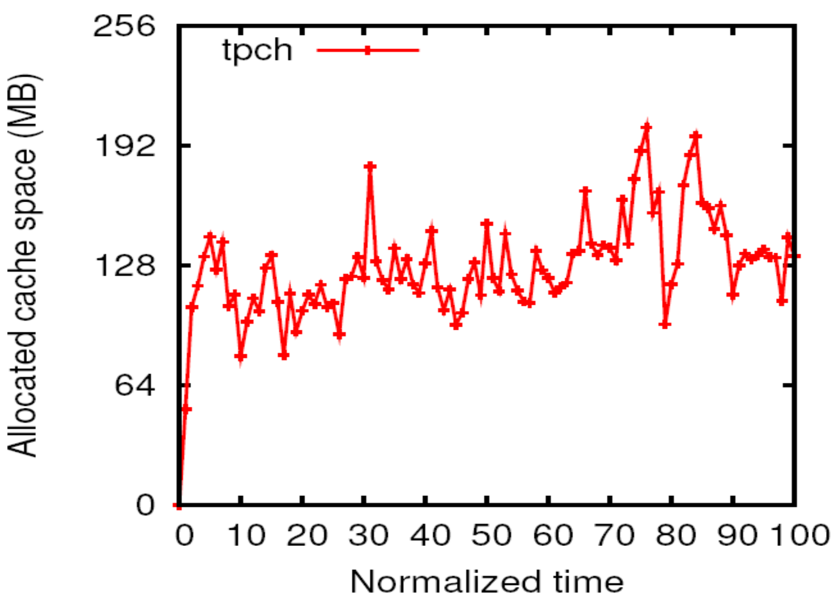


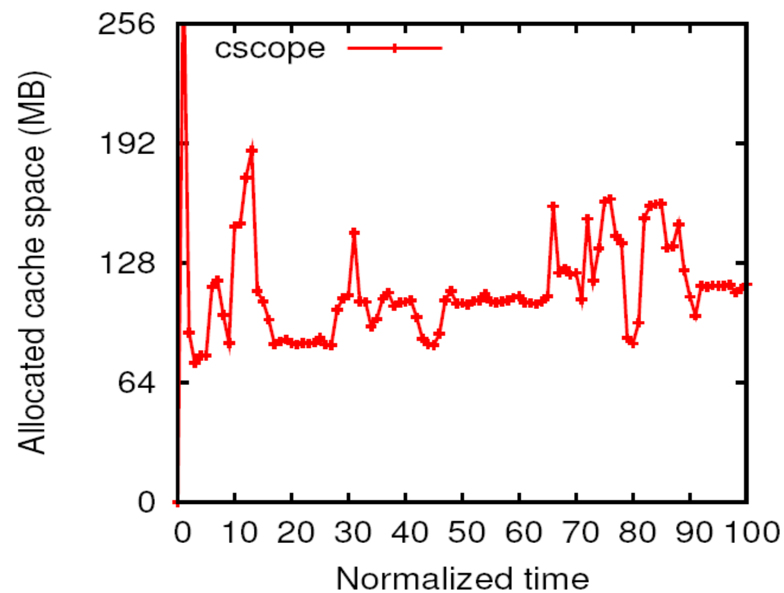
[Supercomputing 2010]

Cache Space Allocations over Time

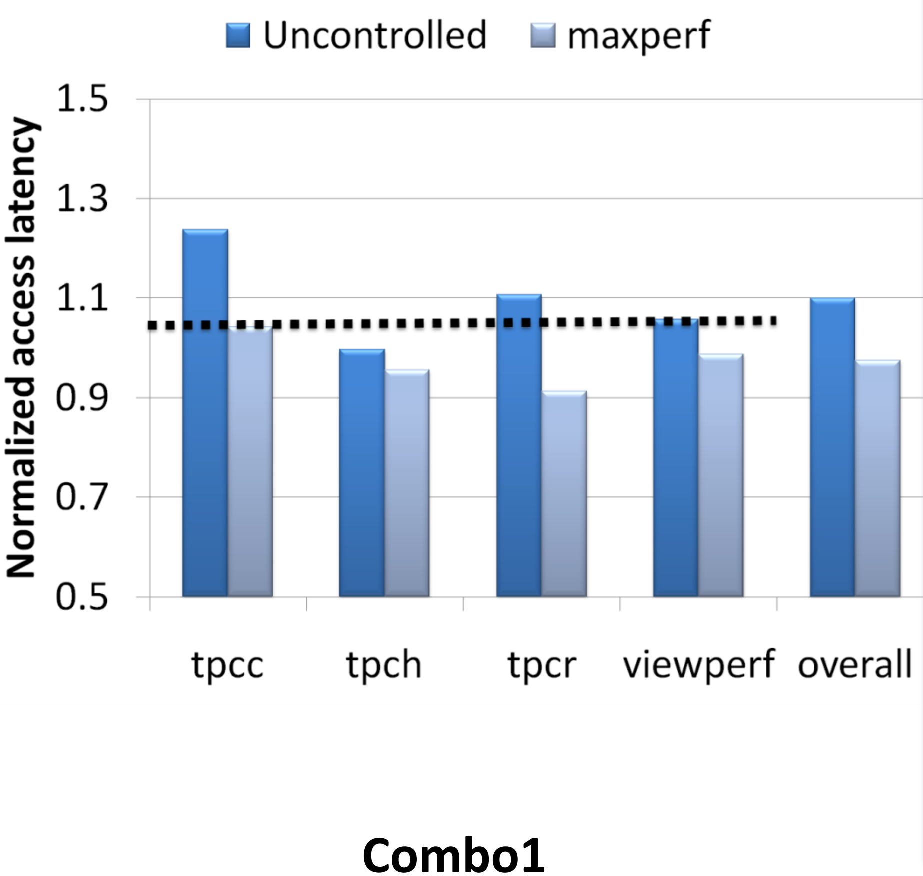


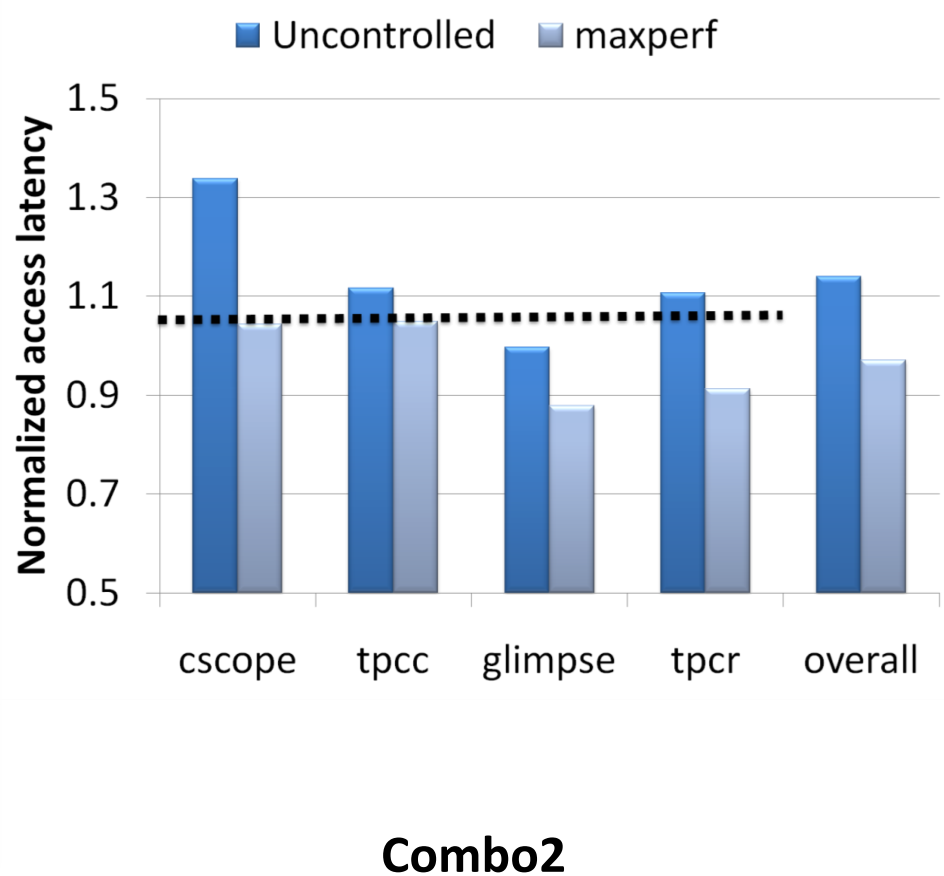






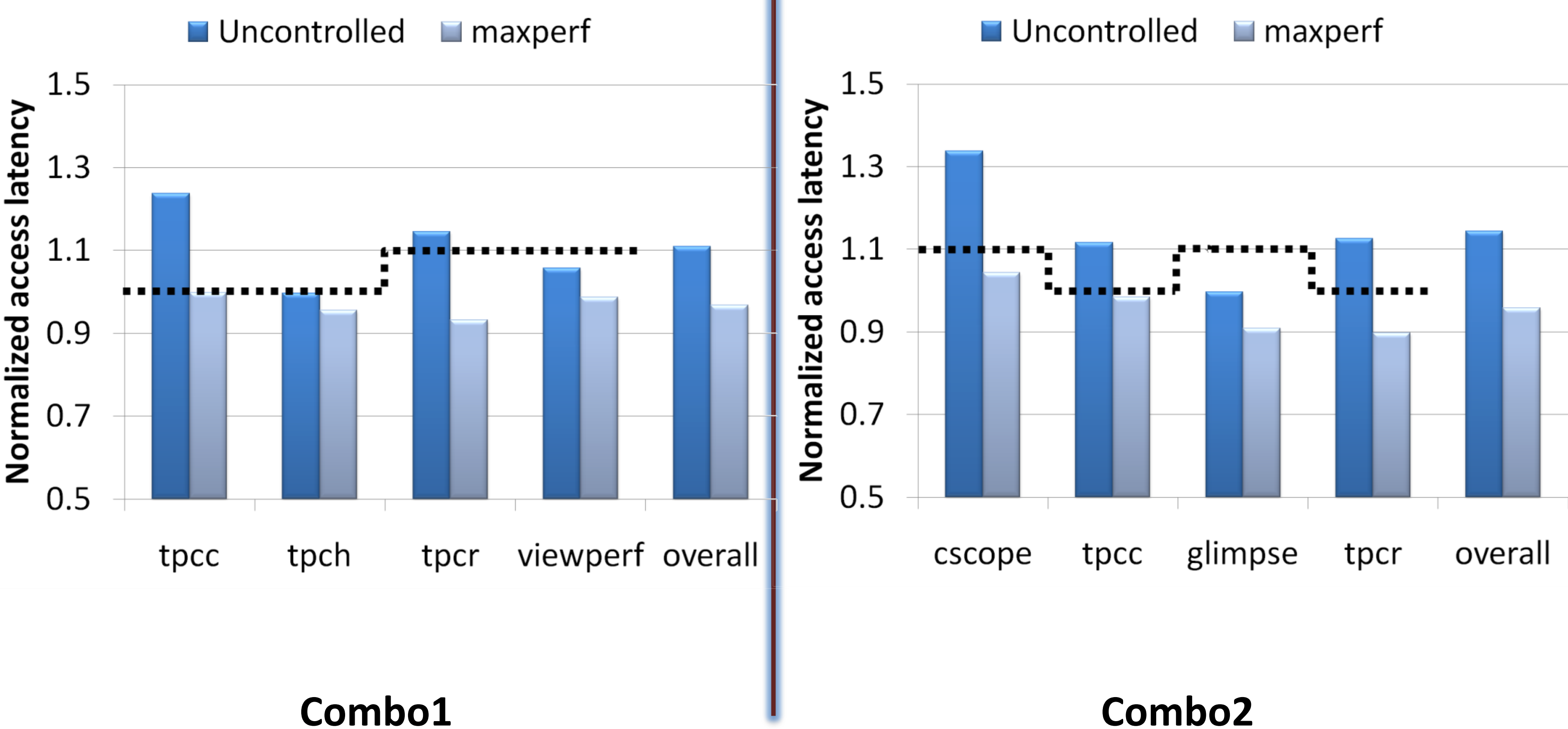
Results and Comparison





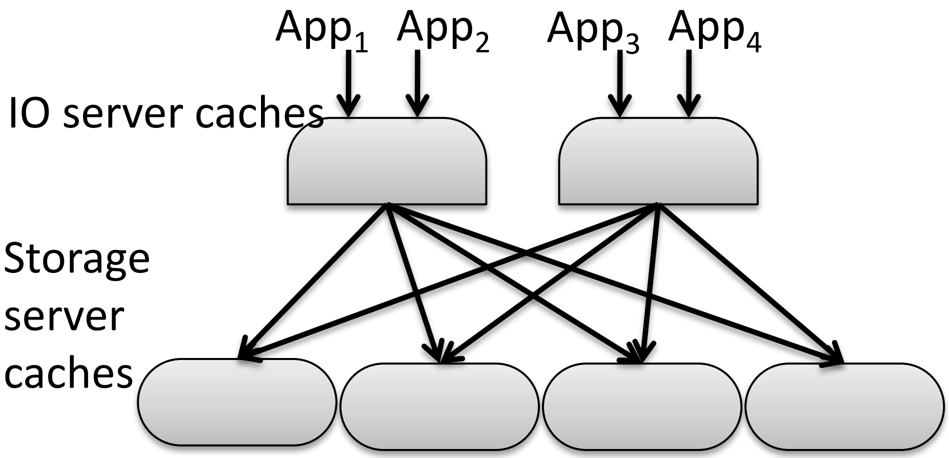
Overall latency improves by 19.6%

Change in SLO Specification

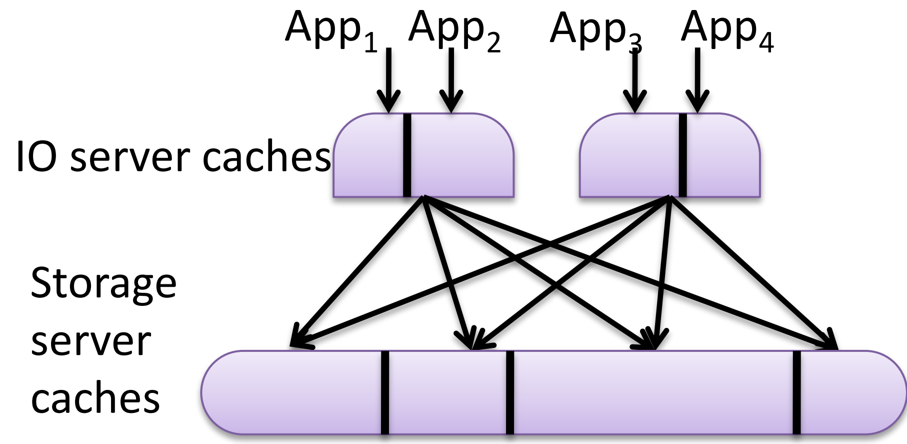


The overall I/O latency improves by up to 20.8%

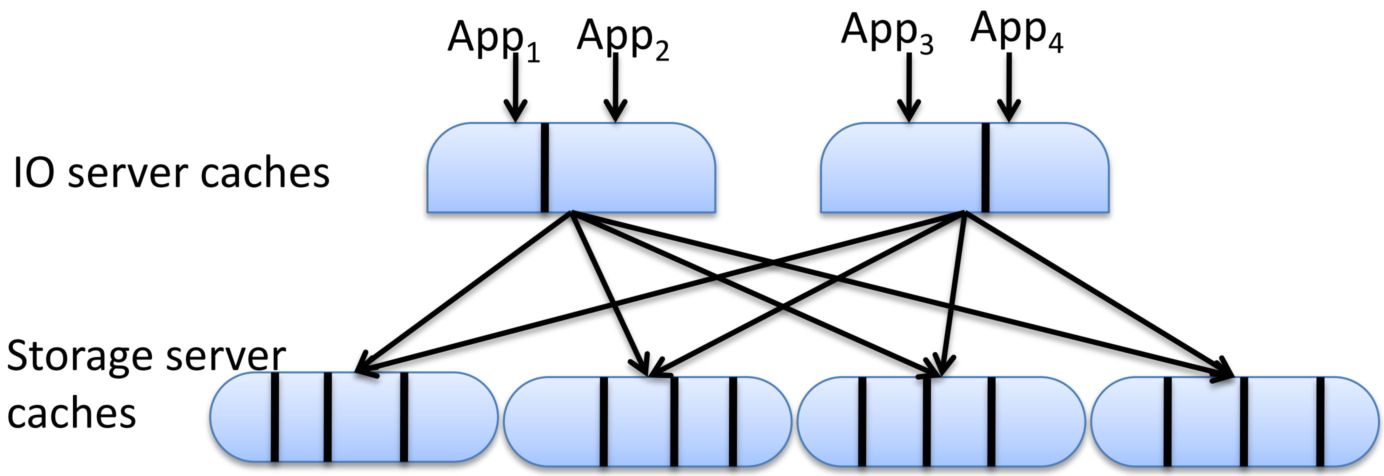
Multi-Level Multi-Server (MLMS) Algorithm



a) Default System



b) Multi-level Partitioning

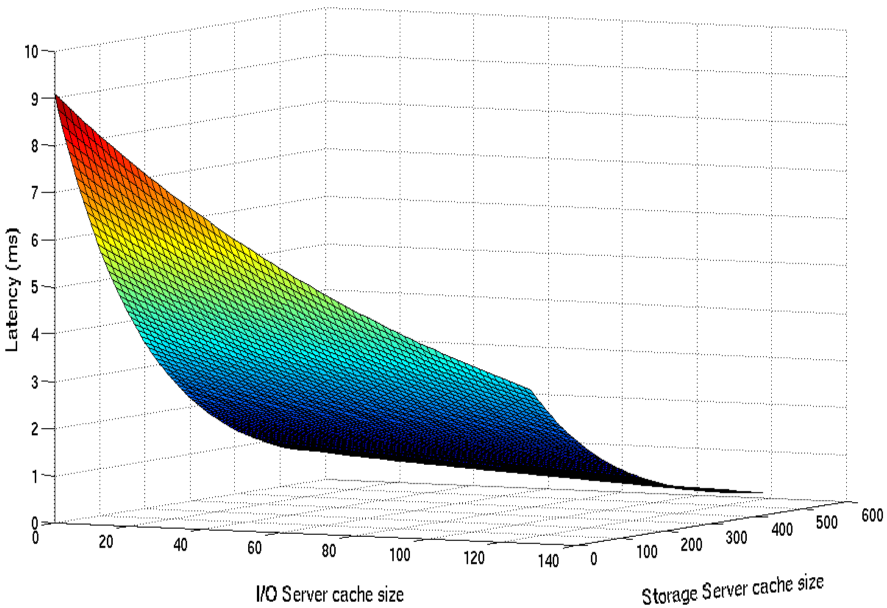


c) Multi-server Partitioning

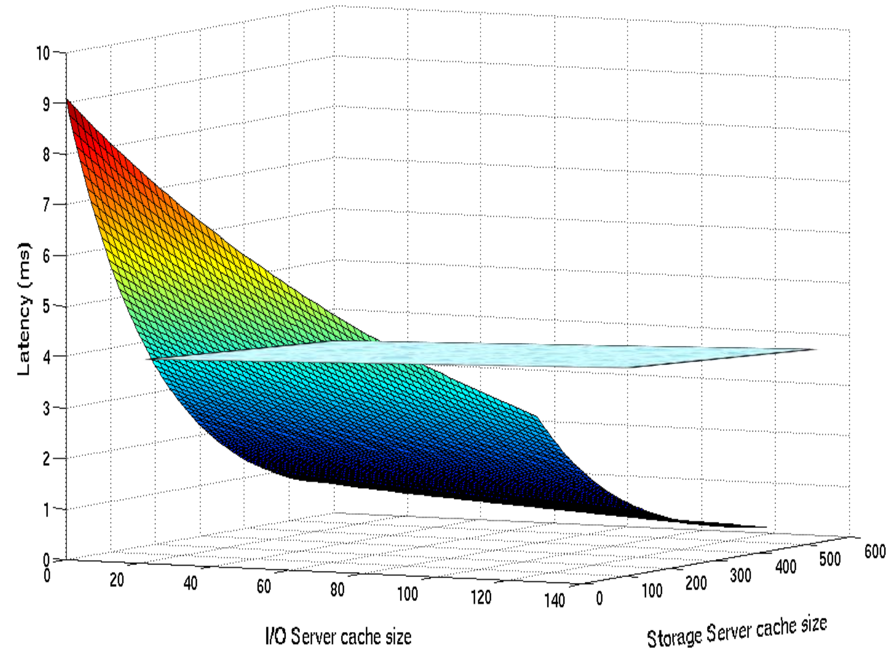
[ICS 2011]

Multi-Level Partitioning

i) Application Characterization



ii) SLO Fulfillment

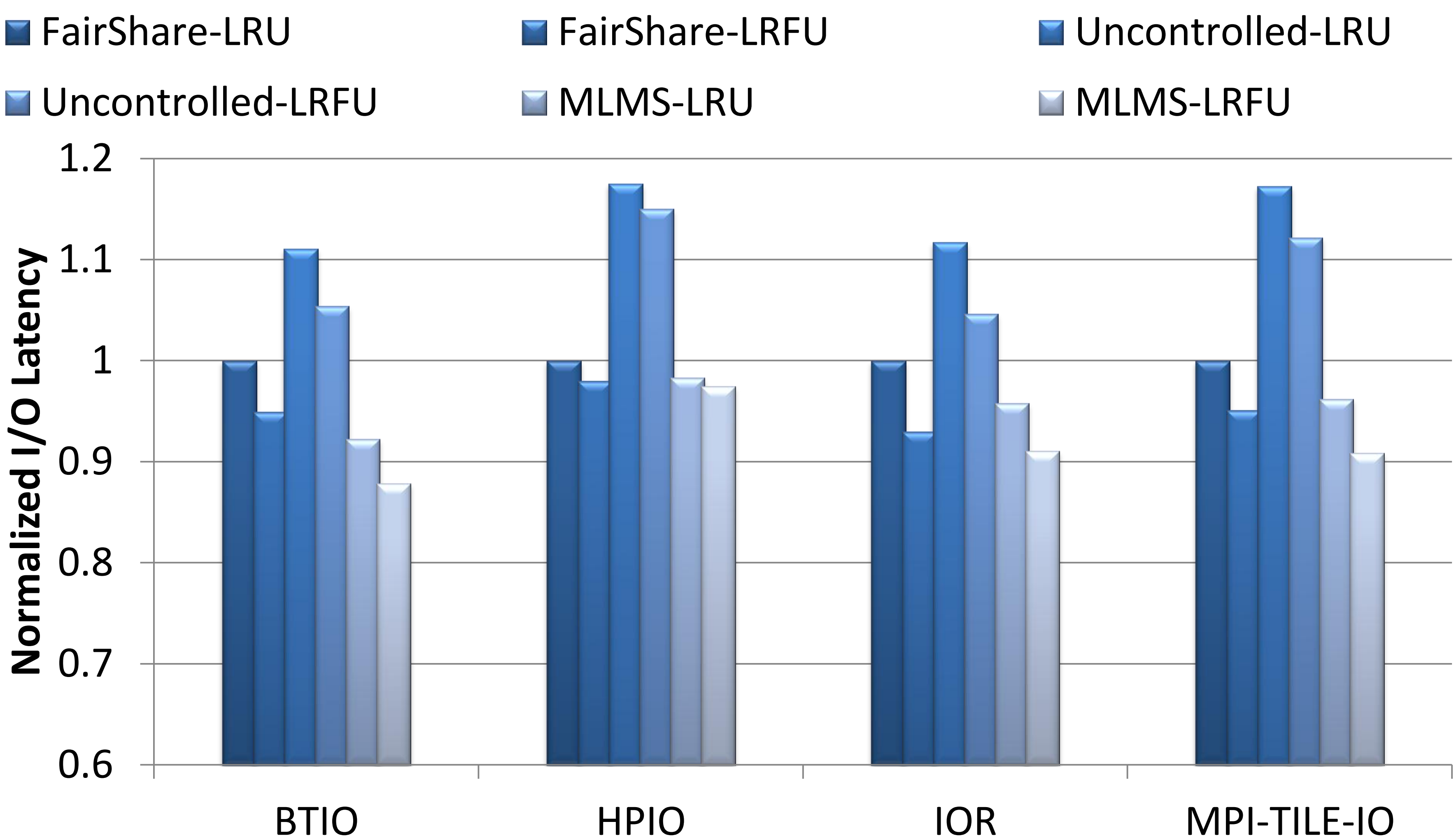


iii) **Determine the feasibility set**: Points that satisfy the SLO of all the applications and are within the physical cache constraints.

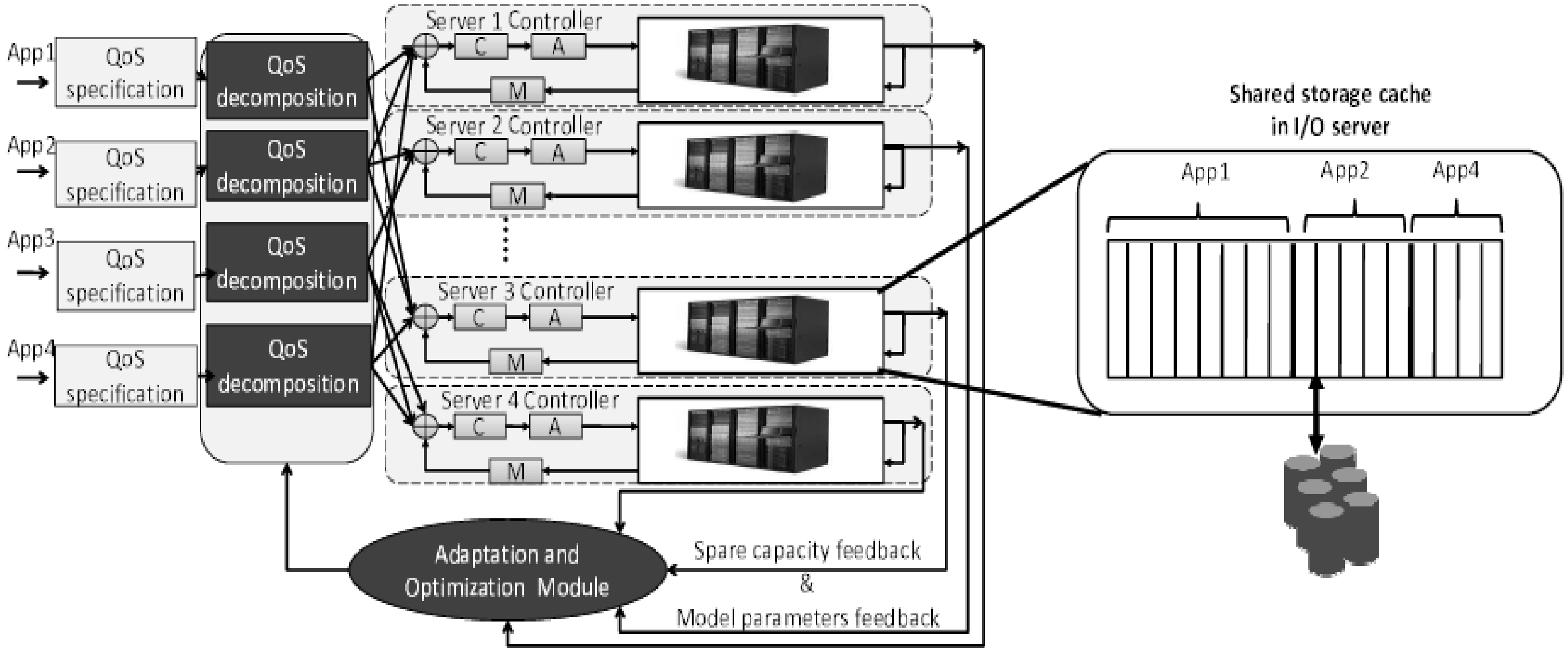
iv) **Maximize the fair-speedup metric (FS)**: Harmonic mean of per application I/O latency improvement with respect to the base scheme (fair share):

$$FS(scheme) = N \,/\, \sum_{j=1}^{N} IOAppj(base) \,/\, IOAppj(scheme)$$

Experimental Results



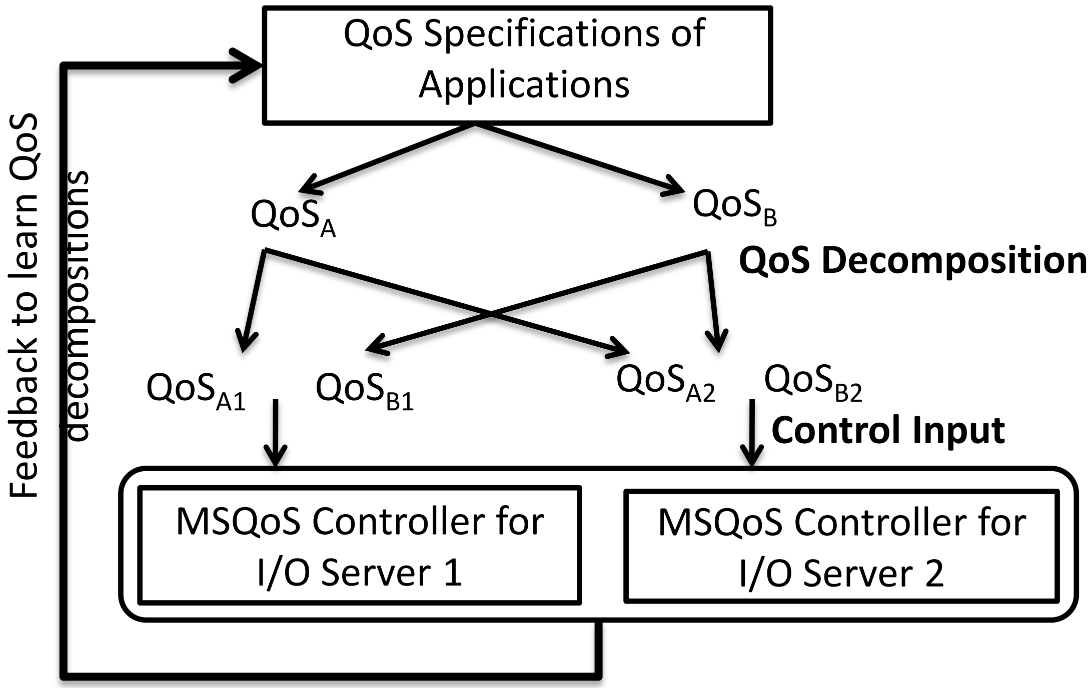
QoS Decomposition and Feedback Control



- ❖ Determines the best QoS decompositions using feedback from each I/O server.
- ❖ The components C, A and M correspond to Controller, Actuator, and QoS Monitor.
- ❖ Each I/O server manages allocation of storage cache among applications accessing it.

[CCGRID 2011]

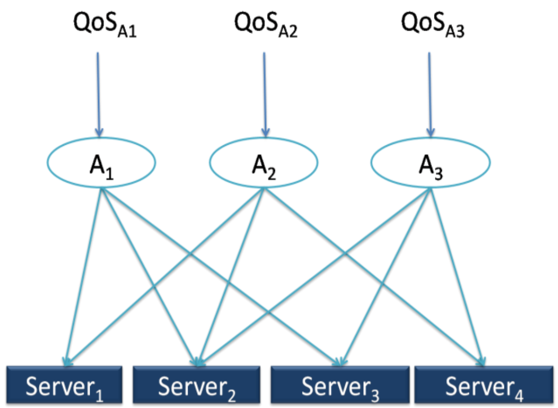
Interactions on Server Nodes



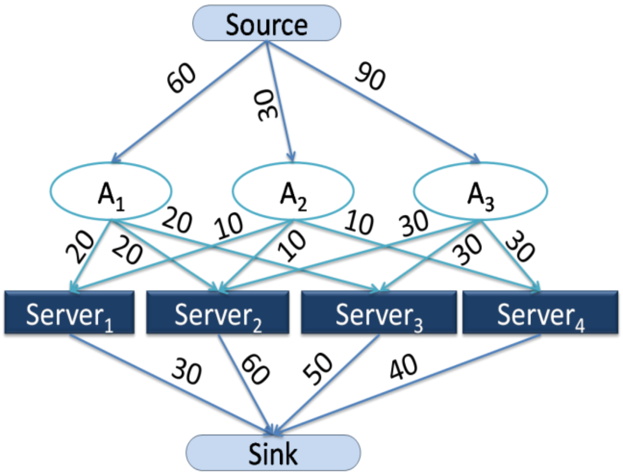
- ❖ Two levels of adaptations in our scheme in a two server system.
- ❖ QoS_{Xi} refers to the sub-QoS of application *X* that has to be satisfied from Server *i*.
- ❖ MSQoS controller manages resources, while decomposition module provides feedback on best QoS decompositions using the max-flow algorithm.

Adaptive QoS Decomposition

QoS specification

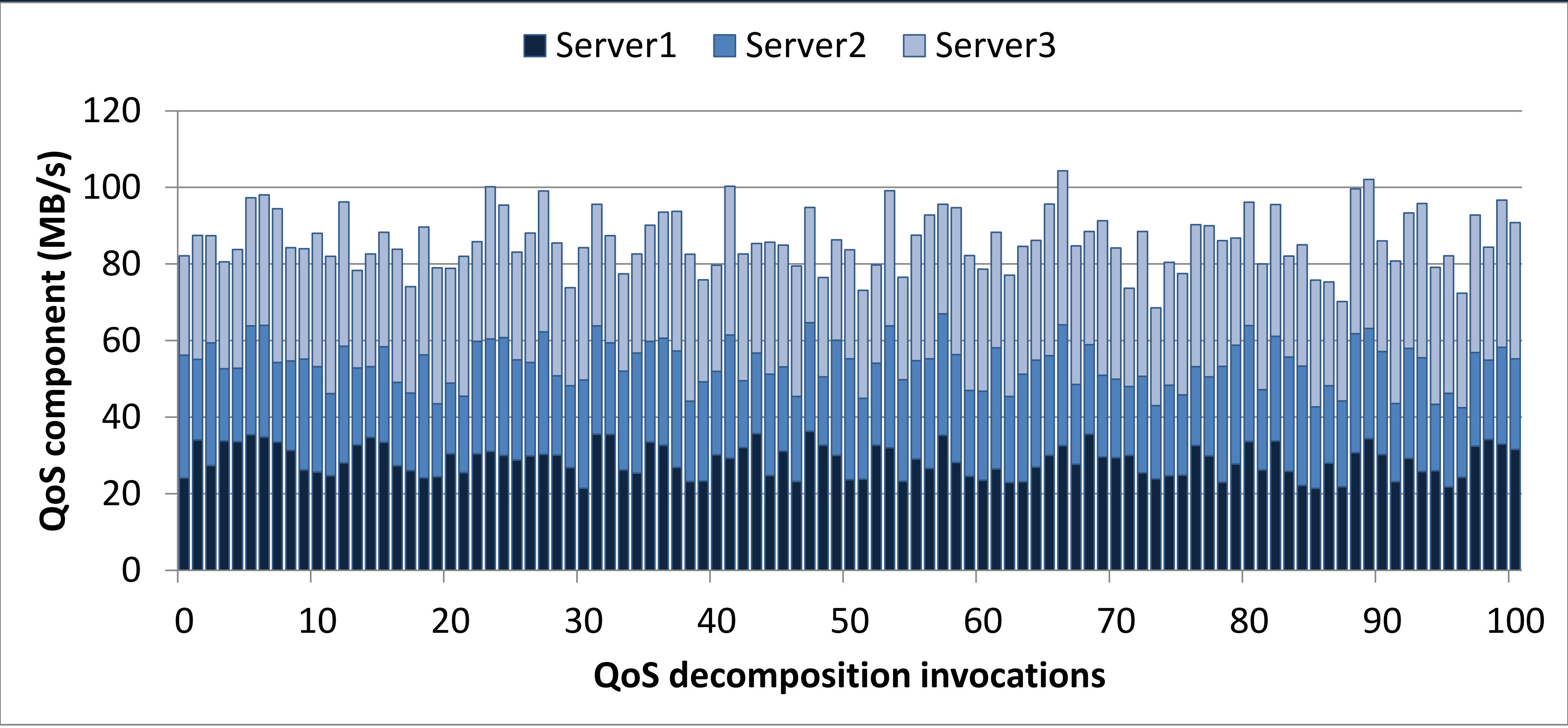


Max-flow algorithm



- ❖ Model the QoS decomposition as a network by adding virtual source and sink
- ❖ Applications and I/O servers form the vertices in the network
- ❖ Run max-flow algorithm

Illustrating QoS Decomposition



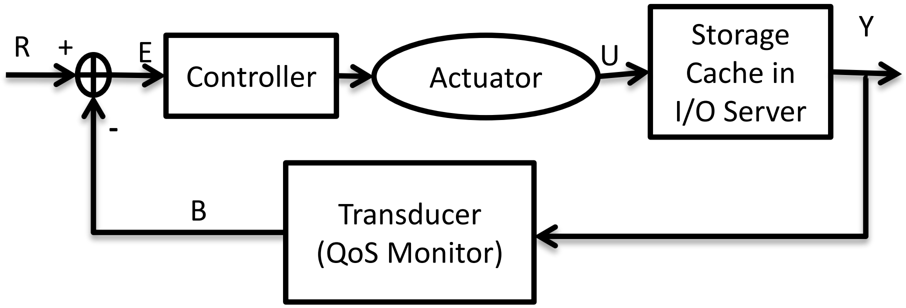
- QoS decomposition of MPI-Tile-IO into servers 1, 2, and 3.

- The dynamics of the decomposition are shown over 100 invocations of the adaptive QoS decomposition scheme.

Feedback Control Theory

Proposed MSQoS controller has **three** main components:

1) Each feedback control loop forms the **Per-Application Controller (PAC) component** of the controller.

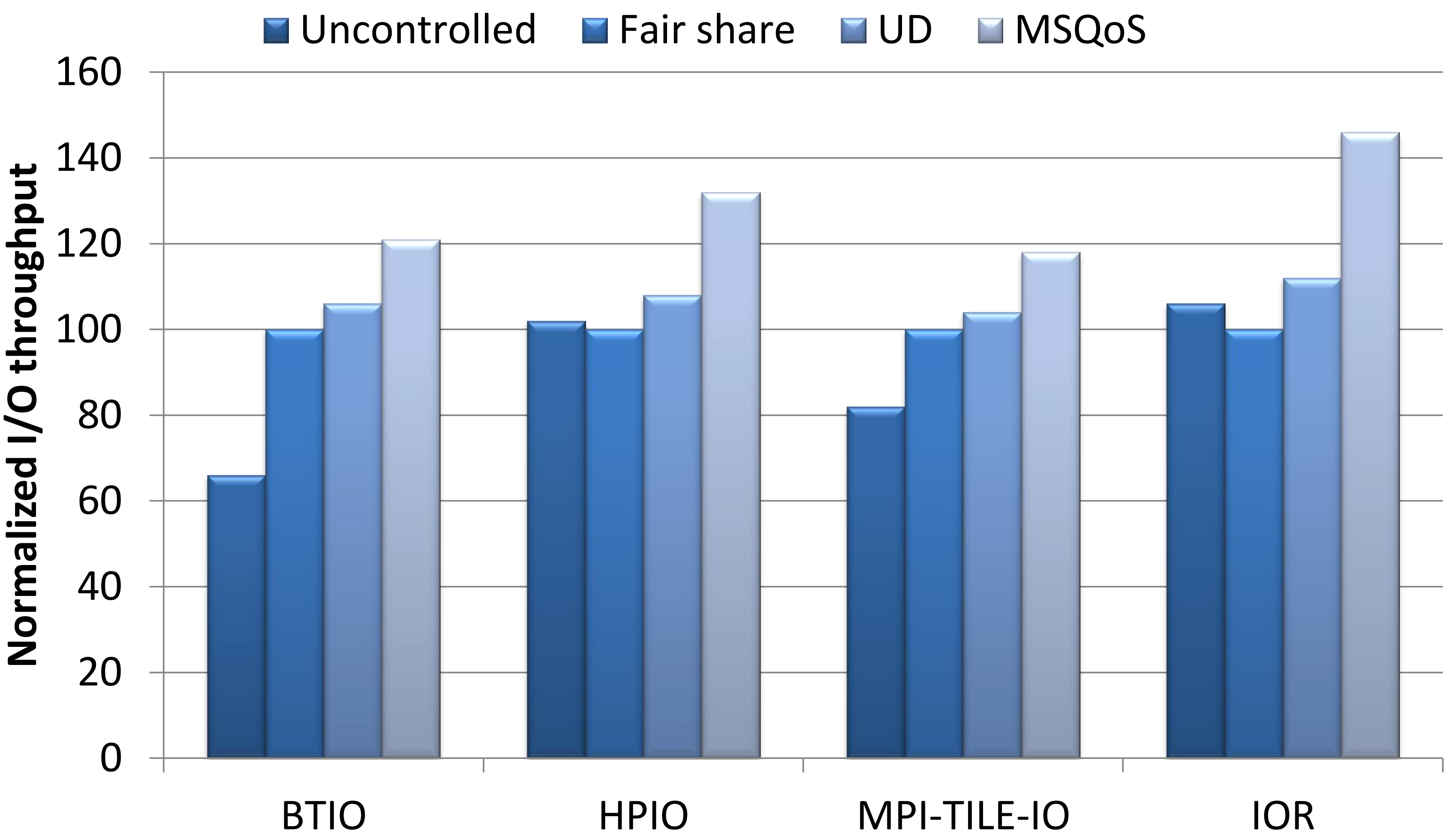


A simple feedback **control loop** for multi-server storage cache management problem.

2) Conflict manager (CM) provides a feasible allocation in each I/O server

3) Target revision component (TRC) of the controller increases the utilization of the storage cache

Experimental Results



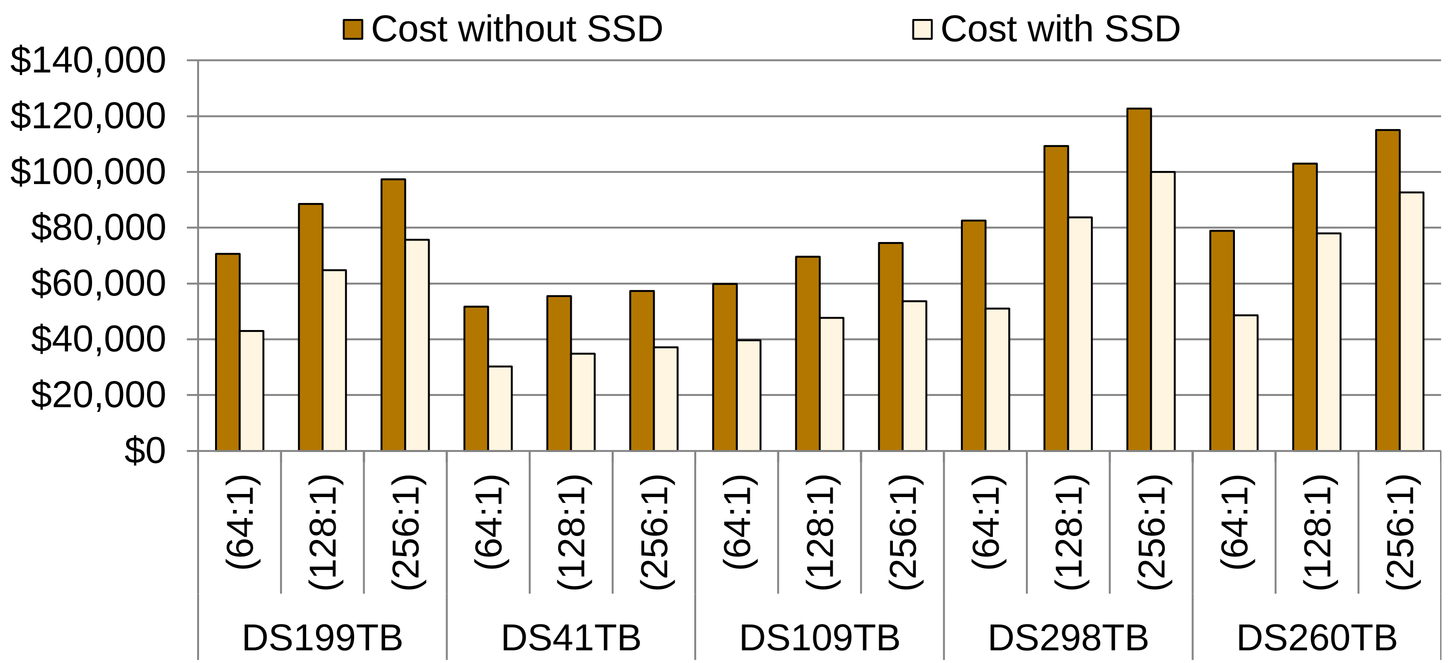
MSQoS improves the throughput of our applications by 48.6%, 29.2%, and 20.7%, respectively, over the uncontrolled partitioning, fair share and uniform decomposition schemes.

SSD Based Provisioning for Checkpointing

- **Staging area**
  - How an intermediate staging area can be positioned in the HPC center to absorb intense checkpoint data
- **Hybrid architecture from node-local resources**
  - A novel multi-tiered staging storage using node-local DRAM and SSD
- **Provisioning and cost/performance model**
  - A provisioning scheme to choose the least-cost storage configuration to meet performance goals
- **Evaluation**
  - Using a large-scale (2400-core) test-bed
  - Simulation study based on six years worth of Jaguar job logs

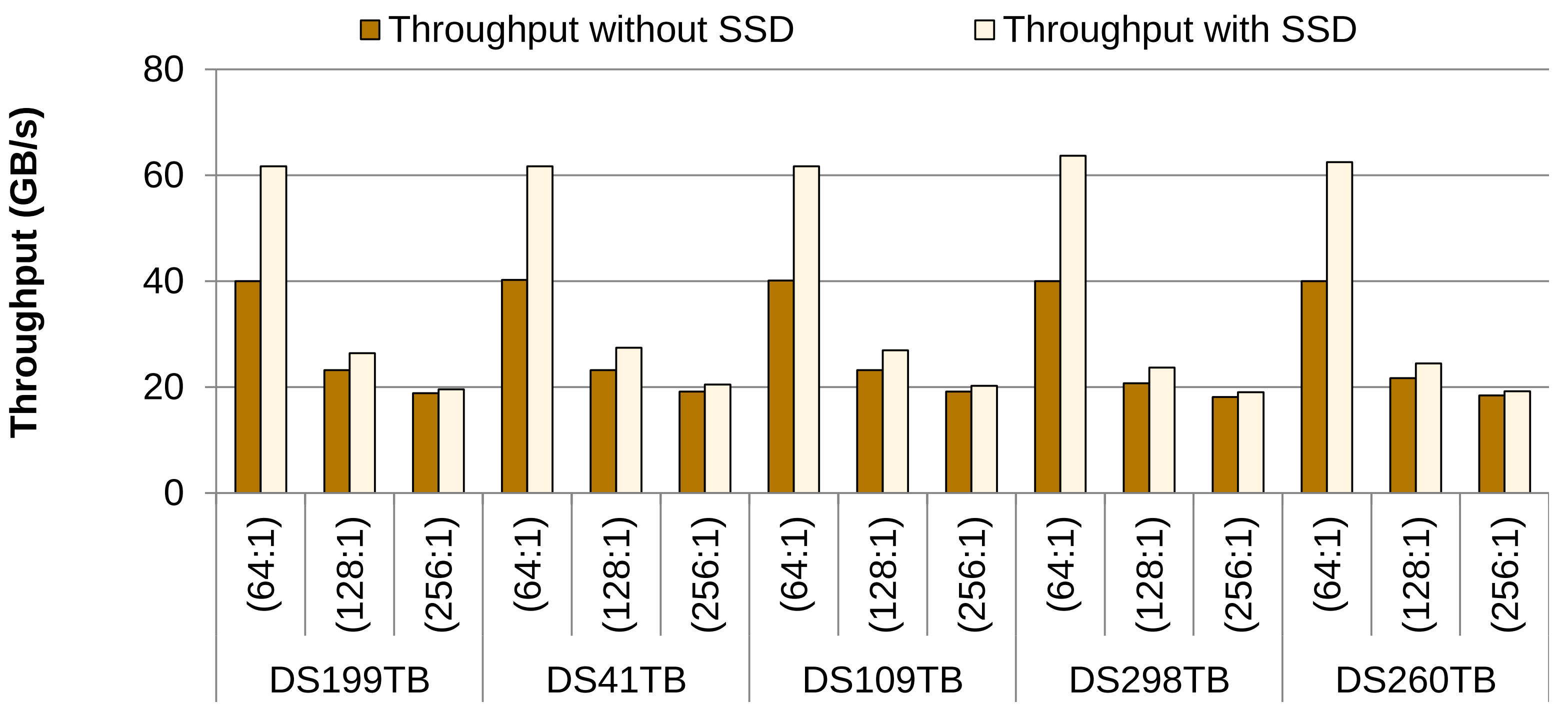
Ramya Prabhakar, Sudharshan Vazhkudai , et al [ICDCS 2011]

Cost Savings in the Staging Area



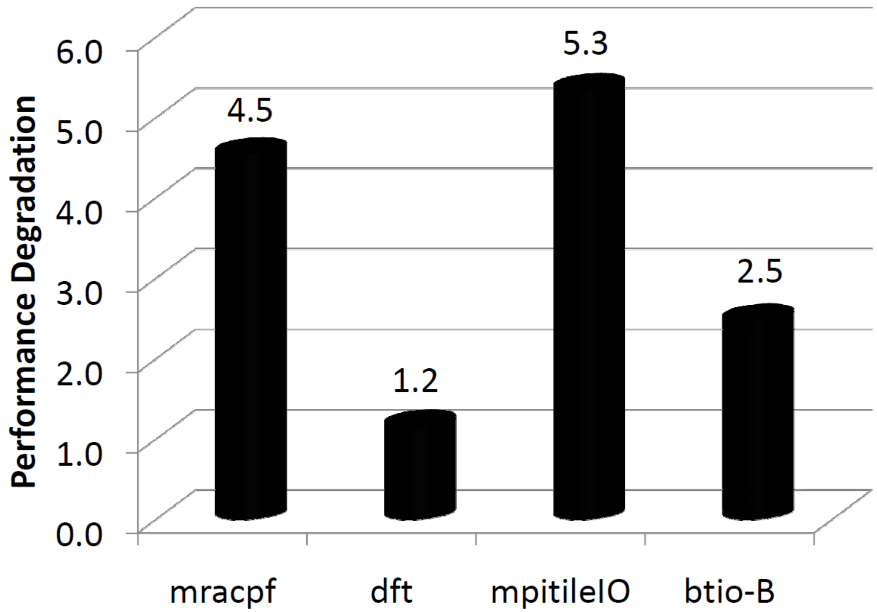
- Five “Hero” jobs, using 200,000+ cores:
  - Center-wide staging model
  - Compute node to staging Node ratios:
    - 64:1, 128:1, 256:1 similar to compute:I/O node ratios
  - If the staging storage is to sustain a throughput of checkpointing in 5 minutes every hour
    - 41.5% cost savings due to our provisioning scheme

Performance under Budget Constraints

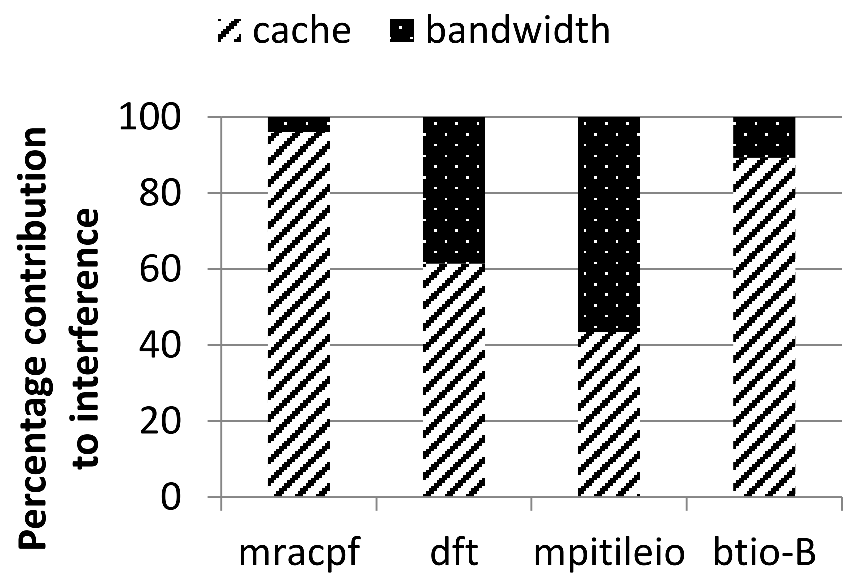


- Budget constraints:
  - For a budget of $90K
    - 59% improvement in throughput in using SSDs in the staging area

Ongoing Work: Coordinated Multi-Resource Partitioning



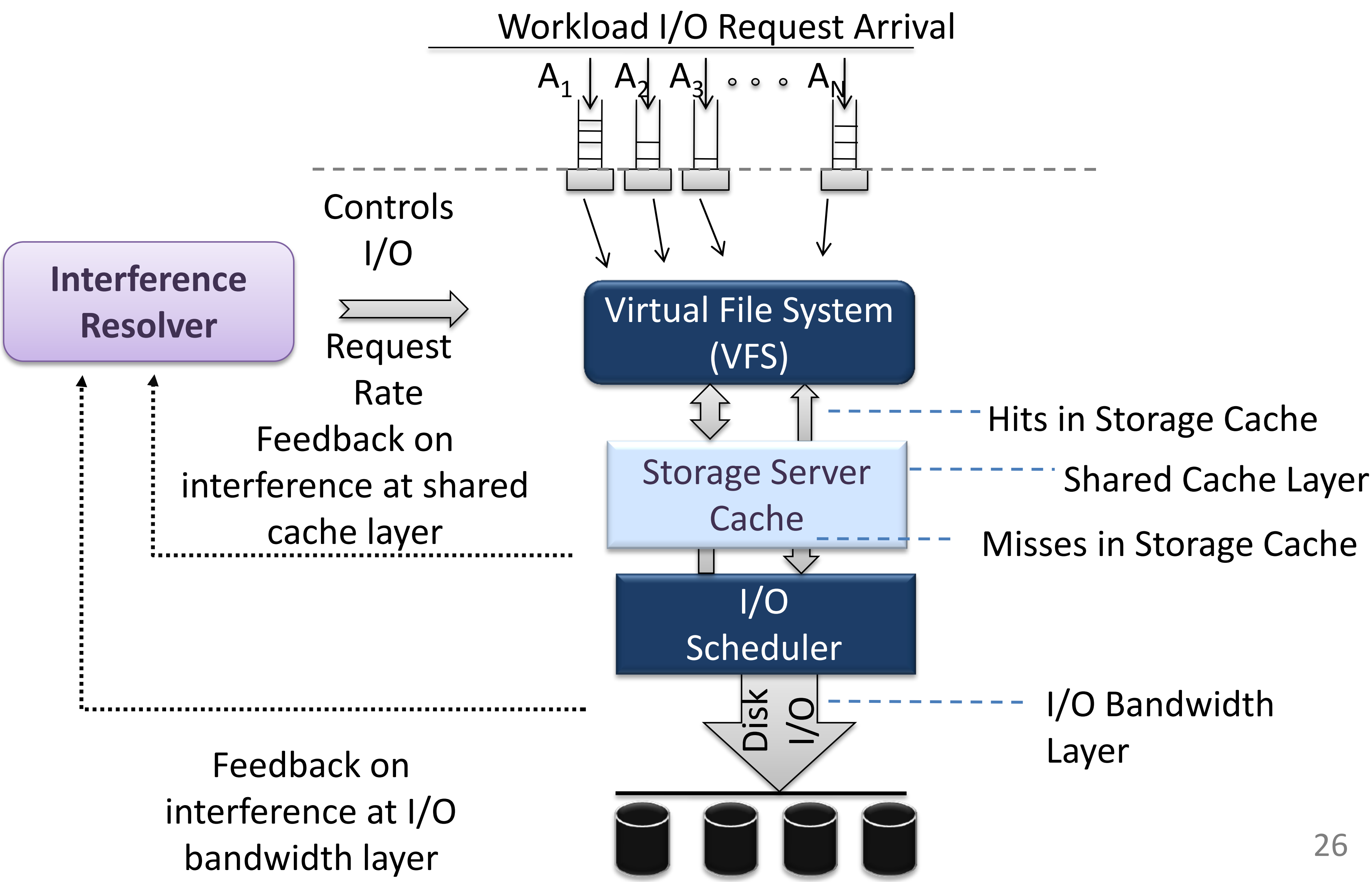
Performance degradation of different concurrently-executing applications on a shared storage system.



Quantifying interferences at both storage cache and I/O bandwidth levels

- Allocation decisions at storage cache directly influence the demand placed on I/O bandwidth
- Independently managing each resource may lead to contradictory decisions
- Motivates need for coordinated resource management scheme

Interference Resolver



Future Work

- End-to-End QoS in hybrid systems
  - Storage subsystem wide
  - Entire architecture wide
- Implementing different feedback control based strategies
- Testing with larger configurations